# CAL Document Change Notification

**DCN No.** 7650-DCN-0098-02

**CHANGE TITLE:** Electronic And Muon Calibration Methods Redefinition

☒ **Internal** ☐ **External**

**ORIGINATOR:** J. Eric Grove **DATE:** 6-Dec-04 **NEXT ASSY:**

| DOC or DWG NUMBER | TITLE | AFFECTED REV. | NEW REV. |
|---|---|---|---|
| LAT-MD-04187 | CAL Electronic And Muon Calibration Definition | 02 | 03 |
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**CHANGE DESCRIPTION:**

1. Corrected errors in contents in calibration suites.
2. Added text to clarify flow of calibration process.

**REASON FOR CHANGE:**

These changes were made to reflect lessons learned from early testing of FM101.

**DISPOSITION OF HARDWARE:**

☐ **No hardware affected**

☒ **Serial numbers affected:** All CAL Modules **Effective date:** 6-Dec-04

| | Use as is | Retest | Rework | Scrap | Other/Comment |
|---|---|---|---|---|---|
| **Raw material** | ☐ | ☐ | ☐ | ☐ | |
| **Parts in process** | ☐ | ☐ | ☐ | ☐ | |
| **Assemblies** | ☒ | ☒ | ☐ | ☐ | FM101 was retested as appropriate to comply. |

| APPROVALS | | DATE | OTHER APPROVALS (specify): | DATE |
|---|---|---|---|---|
| **ORIGINATOR:** | *J. Eric Grove* | 6-Dec-04 | **ELECT ENGINEER:** *James Ampe* | 11-Dec-04 |
| **SUBSYSTEM MANAGER:** | *W. Neil Johnson* | 11-Dec-04 | : | |
| **PROJECT MANAGER:** | *William Raynor* | 11-Dec-04 | : | |
| **QUAL ASSUR. MANAGER:** | *Nick Virmani* | 11-Dec-04 | : | |
| **CONFIGURED AND RELEASED:** | *P. Sandora* | 12-Dec-04 | | |

| GLAST LAT MANAGEMENT DOCUMENT | Document # **LAT-MD-04187-03** | Date Effective 6 Dec 2004 |
|---|---|---|
| | Prepared by(s) J. Eric Grove | Supersedes -02 |
| | Subsystem/Office Calorimeter Subsystem | |
| Document Title **CAL Electronic and Muon Calibration Suite Definition** | | |

# Gamma-ray Large Area Space Telescope (GLAST)

# Large Area Telescope (LAT)

# Calorimeter Flight Model

# Electronic and Muon Calibration Suite Definition

# DOCUMENT APPROVAL

**Prepared by:**

*J. Eric Grove* *6 December 2004*

J. Eric Grove Date
CAL Subsystem Instrument Scientist

**Approved by:**

*W. Neil Johnson* *12 December 2004*

W. Neil Johnson Date
CAL Subsystem Manager

*Nick Virmani* *12 December 2004*

Nick Virmani Date
CAL Subsystem Quality Assurance Manager

*Byron Leas* *12 December 2004*

Byron Leas Date
CAL Subsystem Lead Software Engineer

*James Ampe* *12 December 2004*

James Ampe Date
CAL Subsystem Lead Electrical Engineer

# CHANGE HISTORY LOG

| Revision | Effective Date | Description of Changes |
|---|---|---|
| 01 | 30 Aug 2004 | Initial Release |
| 02 | 10 Nov 2004 | Revised to redistribute unit tests among a new set of suites, calibGen, calibDAC, muTrg, collectMuons, muShape. |
| 03 | 6 Dec 2004 | Corrected errors and missing steps in calibration suites. Reorganized presentation to clarify the calibration flow. |
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# 1 INTRODUCTION

## 1.1 PURPOSE

This document details the sequence and methods to be followed in performing electronic and muon calibrations of the Flight GLAST Calorimeter (CAL) Modules.

## 1.2 SCOPE

The electronic and muon calibrations defined here shall be applied to all Flight CAL Modules during the Assembly and Test sequence at NRL. They shall also be executed during instrument Integration and Test at SLAC, as well as subsequent integration with the spacecraft, although they may be modified to better suite those environments.

## 1.3 APPLICABLE DOCUMENTS

The following documents are applicable to the extent specified within. Unless otherwise indicated, the latest issue in effect shall apply.

| | |
|---|---|
| LAT-SS-00010 | LAT Performance Specification – Level II (b) Specification |
| LAT-SS-00018 | LAT CAL Subsystem Specification - Level III Specification |
| LAT-SS-00210 | LAT CAL Subsystem Specification – Level IV Specification |
| LAT-TD-01502 | LAT Calorimeter Subsystem Test Descriptions |
| LAT-MD-01370 | Calorimeter Functional Test Definition |
| LAT-PS-01513 | Calorimeter Functional Test and Calibration Procedure |

## 1.4 DEFINITIONS AND ACRONYMS

### *1.4.1 Acronyms*

| | |
|---|---|
| CAL | Calorimeter Subsystem of the LAT |
| CDE | Crystal Detector Element |
| GLAST | Gamma-Ray Large Area Space Telescope |
| LAT | Large Area Telescope |
| PDA | PhotoDiode Assembly |
| TBD | To Be Determined |
| TBR | To Be Resolved |

### *1.4.2 Definitions*

| | |
|---|---|
| CAL Tower Module | The integrated Calorimeter Module, Tower Electronics Module, and Tower Power Supply |
| Analysis | A quantitative evaluation of a complete system and/or subsystems by review/analysis of collected data |
| Demonstrate | To prove or show, usually without measurements of instrumentation, that the project/product complies with requirements by observation of the results. |
| Test | A measurement to prove or show, usually with precision measurement or instrumentation, that the product complies with requirements. |
| Validate | To assure the requirement set is complete and consistent, and that each requirement is achievable. |
| Verify | To ensure that the selected solutions meet specified requirements and properly integrate with interfacing products |

# 2 INTRODUCTION

## 2.1 TEST ENVIRONMENT

Electronic and muon calibration of the CAL shall be performed within the LATTE test environment using test scripts and suites maintained under a configuration management system.

Data products and test reports shall be logged to disk in real time and later archived to a long-term storage medium. A description of the CAL data products, test scripts, and test suites can be found in LAT-TD-01502.

The LATTE Environmental Monitoring and Housekeeping shall be enabled at all times during the CAL calibration. Environmental data products shall be logged to disk in real time and later archived to a long-term storage medium. The quantities thus monitored for each CAL Tower Module are the CAL analog and digital 3.3V voltage, the diode bias voltage and current, and one temperature on each of the four AFEE boards.

All calibration shall be executed under approved and released work orders by trained personnel.

## 2.2 TEST PERSONNEL

Test personnel are defined below.

### *2.2.1 Test Director*

The Test Director will have primary responsibility for directing functional test activities. The Test Director will be responsible for coordinating the inputs from the Test Conductor and Quality Assurance representatives, modifying the text script as circumstances dictate, and executing the as-run test approval sheet.

### *2.2.2 Test Conductor*

The Test Conductor will be responsible for monitoring the state of instrument electronics, executing specific functional test activities, and maintaining the test data logbook.

### *2.2.3 Analysis Support*

The Analysis Support will be responsible for analyzing data collected during electrical functional testing and muon performance testing.

# 3 ENERGY CALIBRATION PROCESS

Calibration of the energy scale of the CAL requires calibration of both the electronic gain and non-linearity (i.e. an electronic calibration) and the optical gain of the CDEs (i.e. a muon calibration). The trigger for the muon calibration may be provided either by the CAL or by an external device, e.g. a pair of plastic scintillator paddles.

Energy calibrations at NRL will be generated from both CAL self-triggered muon runs and paddle-triggered muon runs. Because the firing of CAL discriminators introduces a small bias into the energy scale, calibration under self-trigger is a more complicated process, but it has the distinct advantage that no external hardware is required. Thus energy calibrations can be generated for individual CAL Modules at all stages in the environmental test process – including at high and low temperatures during TVAC – and compared one to another. Calibration under paddle or TKR trigger does not suffer from this trigger crosstalk-induced bias and is therefore likely to be more accurate. The final, pre-ship energy calibration of each Module at NRL shall therefore be generated from a muon calibration triggered by a plastic scintillator telescope.

Energy calibration of the integrated LAT prior to launch will be generated by TKR-triggered muon runs.

Detailed analysis of the electronic and muon calibration data is performed in off-line post processing, but simplified analysis routines are defined below for optional *on-line* post processing. This on-line post processing allows calibration constants to be generated for individual CAL Modules during Assembly and Test at stand-alone CTS systems.

## 3.1 ENERGY CALIBRATION UNDER CAL SELF-TRIGGER

Test suites shall be available for calibration of the CAL with the trigger generated by the FLE discriminators. The complete test sequence required to generate an energy calibration under CAL self-trigger is the following.

1. muShape, to find the optimal time-to-peak.
2. calibGen, to calibrate the electronic gain and non-linearity.
3. muTrg, to find the FLE thresholds in energy space.
4. collectMuons, to collect sea-level cosmic muons to calibrate the optical gain.

Once the optimal time-to-peak setting and the FLE thresholds have been determined in a given configuration, the muShape and muTrg steps may be eliminated.

## 3.2 ENERGY CALIBRATION UNDER EXTERNAL TRIGGER

Suites and unit tests shall be available for calibration of the CAL with the trigger generated by an external source, e.g. plastic scintillator paddles or the TKR. The complete test sequence required to generate an energy calibration under external trigger is the following.

1. extShape, to find the optimal time-to-peak for externally triggered muons.
2. calibGen, to calibrate the electronic gain and non-linearity.
3. collectExt, to collect externally-triggered muons to calibrate the optical gain.

Once the optimal time-to-peak setting has been determined in a given configuration, the extShape step may be eliminated. The calibGen execution may be taken from a recent energy calibration under CAL trigger. Furthermore, during energy calibration of the integrated LAT at SLAC, the calibGen may be abbreviated to include only those settings that duplicate the flight FLE thresholds.

# 4 ELECTRONIC CALIBRATION PROCESSES

## 4.1 PURPOSE OF ELECTRONIC CALIBRATION

Electronic calibration of each GCFE is provided by a series of internal charge-injection processes. The goal of these processes is a set of calibration tables that give the correspondence between relevant DAC setting and output ADC bin (or energy, once the optical gain is known).

- Pedestal centroid and width for all energy ranges in all gain settings. An estimate of the electronic noise can be derived from the pedestal width.
- Front-end transfer function for all energy ranges, i.e. the integral non-linearity of the analog and digital chain for each energy range. The electronic gain of each energy range is given by the linear term of the correspondence between injected charge and output ADC bin.
- Calibration of the low-energy discriminator (FLE) DAC.
- Calibration of the high-energy discriminator (FHE) DAC.
- Calibration of the zero-suppression threshold (LAC) DAC.
- Calibration of the auto-ranging discriminator (ULD) DAC.

Units of the calibration tables can be converted to MeV in all gain settings through the *adc2nrgy* and *relgain* tables. Software tools shall be provided to make this conversion and to generate command tables to set these parameters in energy units.

## 4.2 DEFINITION OF ELECTRONIC CALIBRATION SUITES

The electronic calibration of the CAL is accomplished with a pair of test suites, each of which is comprised of a series test scripts that form a suite executed under LATTE. The suites, calibGen and calibDAC, are outlined below as ordered lists of scripts.

The purpose of the calibGen suite is to provide calibration of the front-end transfer function for all energy ranges. In combination with the muon calibration, the energy calibration can be derived.

The purpose of the calibDAC suite is to provide complete calibration of all settings of the configuration DACs. The calibDAC suite repeats the characterizations of the FLE, FHE, LAC, and ULD DACs generated in the CPT (see LAT-PS-01370), and indeed differs only in that it tests all DAC settings, rather than a subset. Thus calibDAC need not be executed frequently, and it is not required for energy calibration or proper functioning of the CAL.

### *4.2.1 Outlines of the electronic calibration suites*

The motivation for each suite is given in this section and its subsections, along with a description of the script algorithms and configurations. A detailed definition of each script is given in LAT-TD-01502.

For each GCFE, the calibGen suite shall provide calibration of the electronic gain and integral nonlinearity of all four energy ranges. Data shall be taken in several configurations such that the distortion induced in the four energy ranges by the FLE and FHE discriminator firing may be measured and accounted for in subsequent energy calibrations. The suite shall be comprised of the following test procedures. As defined herein, they are executed sequentially on a single CAL Tower Module. At all times during the execution of the suite, Environmental Monitoring and Housekeeping shall be enabled.

1. CALU_INIT: Initialize the Calorimeter.
2. CALF_TRG_P03: Characterize the FLE DAC settings with charge injection (if required by WOA).
3. genFLEsettings_ADC: Generate FLE DAC settings corresponding to ~5 MeV (if CALF_TRG_P03 has been run).
4. CALU_INIT: Load FLE DAC setting and characterization tables, (if generated in previous step).

5. CALF_COLLECT_CI_SINGLEX16: Determine front-end integral non-linearity and noise with charge injection. Set FLE DACs to ~5 MeV and Tack delay to optimal value for charge injection.
6. CALF_COLLECT_CI_SINGLEX16: Determine front-end integral non-linearity and noise with charge injection. Set FLE DACs to their maximum value and Tack delay to optimal value for charge injection.
7. CALF_COLLECT_CI_SINGLEX16: Determine front-end integral non-linearity and noise with charge injection. Set FLE DACs to ~5 MeV and Tack delay to optimal value for muons.
8. CALF_COLLECT_CI_SINGLEX16: Determine front-end integral non-linearity and noise with charge injection. Set FLE DACs to their maximum value and Tack delay to optimal value for muons.
9. CALF_COLLECT_CI_SINGLEX16: Determine front-end integral non-linearity and noise with charge injection. Set FLE DACs to their maximum value and Tack delay to optimal value for charge injection. Inject into HE channel only.
10. CALF_COLLECT_CI_SINGLEX16: Determine front-end integral non-linearity and noise with charge injection. Set FLE DACs to their maximum value and Tack delay to optimal value for charge injection. Inject into LE and HE channels. Configure for cross-calibration between LE and HE.

The calibGen suite runs to completion in ~2 hours.

For each GCFE, the calibDAC suite shall provide calibration of the relative electronic gain of all four energy ranges, the FLE and FHE discriminator settings, the LAC discriminator setting, and the range ULD settings. The calibration is performed in the flight gain settings. The suite shall be comprised of the following test procedures. As defined herein, they are executed sequentially on a single CAL Tower Module. At all times during the execution of the suite, Environmental Monitoring and Housekeeping shall be enabled.

1. CALU_INIT: Initialize the Calorimeter.
2. CALF_PEDESTALS_CI: Compute pedestals.
3. CALU_INIT: Redefine pedestal table.
4. CALF_GAIN_P01: Calibrate electronic gains with charge injection. Generate *relgain* table.
5. CALU_INIT: Redefine *relgain* table.
6. CALF_TRG_P03: Calibrate FLE and FHE DAC settings with charge injection. Generate *fle2adc* and *fhe2adc* tables.
7. CALF_SUPP_P01: Calibrate LAC DAC settings with charge injection. Generate *lac2adc* table.
8. CALF_RNG_P01: Calibrate ULD DAC settings with charge injection. Generate *uld2adc* table.

The calibDAC suite runs to completion in ~8 hours.

### *4.2.2 calibGen suite*

The calibGen suite comprises a sequence of 10 unit tests.

**1. CALU_INIT: Initialize the Calorimeter**

The CAL initialization script shall be executed to ensure that the CAL is powered and begins the calibration suite in a defined configuration.

The default CAL test configuration is given in Table 1 below.

| **Parameter** | **Configuration** |
|---|---|
| Diode bias | On, DAC set to 3072 (0xC00), equates to approx. 75 volts. 20 second wait is implemented to ensure bias has stabilized if setting change is needed |
| GCCC config | Configuration = 0x80090906 (per SLAC direction)<br>Layer_mask_0/1 set based on schema<br>FIFO_Status is cleared<br>Latched Status is cleared<br>Event Timeouts = 0<br>Trg_alignment = 0xa0f00 (per SLAC suggestion). |

| | |
|---|---|
| GCRC config | Delay_1 = nominal (30 clock tics with 20 MHz Clock)<br>Delay_2 = nominal (60 clock tics with 20 MHz Clock)<br>Delay_3 = nominal (144 clock tics with 20 MHz Clock) |
| GCFE config | FLE DAC = 127;<br>FHE DAC = 127;<br>LAC DAC = 127;<br>ULD DAC = 127;<br>REF_DAC = 127.<br>Config_0 = 0<br>Config_1 = 0 |
| PDU config | CAL Analog voltage DAC = 2048 (3.3V) nominal<br>CAL Digital voltage DAC = 2048 (3.3V) nominal |
| Miscellaneous | Clock Frequency (saved for time calculations) |

Table 1: Default CAL configuration

**2. CALF_TRG_P03: Calibrate the FLE DAC settings with charge injection (if required by WOA).**

The pulse amplitudes at which the FLE discriminators fire at muon gain shall be calibrated with charge injection.

This test shall be performed in muon gain (LE = 5; HE = 0). For each column of GCFEs sequentially, the FLE DAC shall be set to each of the 128 settings spanning fine and coarse ranges, and the charge-injection DAC shall be ramped upward in steps of 3 DAC units, with a small number of pulses (~30) generated at each amplitude. The trigger diagnostic data shall be inspected to determine if the FLE discriminators have fired. If the FLE fires for >50% of the pulses, the corresponding mean ADC value shall be recorded.

The output of this process is a table of correspondence between FLE DAC setting and ADC bin number in the muon gain ("*fle2adc*"). This table shall be identified as having been created in muon gain.

Note that this calibration is not a precise calibration of the discriminator thresholds in energy units because the charge injection pulse shape is not identical to the scintillation pulse shape; the ratio of fast-shaped to slow-shaped signals is therefore different for charge injection pulses than for scintillation pulses. The correspondence into energy units is calibrated with the muTrg suite.

**3. genFLEsettings_ADC: Generate FLE DAC settings corresponding to ~5 MeV (if CALF_TRG_P03 has been run).**

Using the characterization tables created by the preceding CALF_TRG_P03, a table of FLE DAC settings corresponding to ~5 MeV shall be generated. Because the muon peak of ~11 MeV energy deposition typically corresponds to ~330 LEX8 ADC bins at LE gain 5, the value of "5 MeV" shall be defined to 150 LEX8 ADC bins above pedestal to this suite.

**4. CALU_INIT: Load FLE DAC setting and characterization tables (if generated in previous step).**

The FLE DAC settings and characterization tables just generated shall be loaded.

**5. CALF_COLLECT_CI_SINGLEX16: Determine front-end integral non-linearity and noise with charge injection. Set FLE DACs to ~5 MeV and Tack delay to optimal value for charge injection.**

The electronic gain scale of each energy range shall be measured with charge-injection data. Charge shall be injected simultaneously into a limited number of GCFE chips to minimize the bias introduced into the gain and linearity measurement by cross talk between neighboring GCFEs. This test shall be performed with the FLE DAC set to ~5 MeV. The electronic gain scale should then correspond to that observed when muons are collected with FLE DAC set to ~5 MeV.

This test shall be performed in muon gain (LE = 5; HE = 0) with the Tack delay set to the optimal value for charge injection with solicited triggers. A modest number of pulses (~50) shall be generated at amplitudes spanning the LEX1 range in a pattern chosen to map the known regions of non-linearity. The default pattern sets the charge injection DAC from 0 to 64 in steps of 2, 80 to 512 in steps of 16, and 543 to 4095 in steps of 32. To maximize the information gathered for subsequent analysis, all four energy ranges shall be read out in commanded-range order

(LEX8 first), and zero-suppression shall be disabled. Charge is injected simultaneously into one column of four GCFEs on each AFEE board.

6. **CALF_COLLECT_CI_SINGLEX16: Determine front-end integral non-linearity and noise with charge injection. Set FLE DACs to their maximum value and Tack delay to optimal value for charge injection.**

The electronic gain scale of each energy range shall be measured with charge-injection data. Charge shall be injected simultaneously into a limited number of GCFE chips to minimize the bias introduced into the gain and linearity measurement by cross talk between neighboring GCFEs. This test shall be performed with the FLE DAC set to 127, the maximum possible value. The electronic gain scale should then correspond to that observed when muons are collected with FLE DAC set to 127 (i.e. close to the flight setting).

This test shall be performed in muon gain (LE = 5; HE = 0) with the Tack delay set to the optimal value for charge injection with solicited triggers. A modest number of pulses (~50) shall be generated at amplitudes spanning the LEX1 range in a pattern chosen to map the known regions of non-linearity. The default pattern sets the charge injection DAC from 0 to 64 in steps of 2, 80 to 512 in steps of 16, and 543 to 4095 in steps of 32. To maximize the information gathered for subsequent analysis, all four energy ranges shall be read out in commanded-range order (LEX8 first), and zero-suppression shall be disabled. Charge is injected simultaneously into one column of four GCFEs on each AFEE board.

7. **CALF_COLLECT_CI_SINGLEX16: Determine front-end integral non-linearity and noise with charge injection. Set FLE DACs to ~5 MeV and Tack delay to optimal value for muons.**

The electronic gain scale of each energy range shall be measured with charge-injection data. Charge shall be injected simultaneously into a limited number of GCFE chips to minimize the bias introduced into the gain and linearity measurement by cross talk between neighboring GCFEs. This test shall be performed with the FLE DAC set to ~5 MeV. The electronic gain scale should then correspond to that observed when muons are collected with FLE DAC set to ~5 MeV.

This test shall be performed in muon gain (LE = 5; HE = 0) with the Tack delay set to the optimal value for CAL self-triggered muons. A modest number of pulses (~50) shall be generated at amplitudes spanning the LEX1 range in a pattern chosen to map the known regions of non-linearity. The default pattern sets the charge injection DAC from 0 to 64 in steps of 2, 80 to 512 in steps of 16, and 543 to 4095 in steps of 32. To maximize the information gathered for subsequent analysis, all four energy ranges shall be read out in commanded-range order (LEX8 first), and zero-suppression shall be disabled. Charge is injected simultaneously into one column of four GCFEs on each AFEE board.

8. **CALF_COLLECT_CI_SINGLEX16: Determine front-end integral non-linearity and noise with charge injection. Set FLE DACs to their maximum value and Tack delay to optimal value for muons.**

The electronic gain scale of each energy range shall be measured with charge-injection data. Charge shall be injected simultaneously into a limited number of GCFE chips to minimize the bias introduced into the gain and linearity measurement by cross talk between neighboring GCFEs. This test shall be performed with the FLE DAC set to 127, the maximum possible value. The electronic gain scale should then correspond to that observed when muons are collected with FLE DAC set to 127 (i.e. close to the flight setting).

This test shall be performed in muon gain (LE = 5; HE = 0) with the Tack delay set to the optimal value for CAL self-triggered muons. A modest number of pulses (~50) shall be generated at amplitudes spanning the LEX1 range in a pattern chosen to map the known regions of non-linearity. The default pattern sets the charge injection DAC from 0 to 64 in steps of 2, 80 to 512 in steps of 16, and 543 to 4095 in steps of 32. To maximize the information gathered for subsequent analysis, all four energy ranges shall be read out in commanded-range order (LEX8 first), and zero-suppression shall be disabled. Charge is injected simultaneously into one column of four GCFEs on each AFEE board.

9. **CALF_COLLECT_CI_SINGLEX16: Determine front-end integral non-linearity and noise with charge injection. Set FLE DACs to their maximum value and Tack delay to optimal value for charge injection. Inject into HE channel only.**

The electronic gain scale of the HE energy ranges shall be measured with charge-injection data. Charge shall be injected simultaneously into a limited number of GCFE chips to minimize the bias introduced into the gain and linearity measurement by cross talk between neighboring GCFEs. This test shall be performed with the FLE DAC set to 127, the maximum possible value.

This test shall be performed in muon gain (LE = 5; HE = 0) with the Tack delay set to the optimal value for charge injection with solicited triggers. A modest number of pulses (~50) shall be generated at amplitudes spanning the LEX1 range in a pattern chosen to map the known regions of non-linearity. The default pattern sets the charge injection DAC from 0 to 64 in steps of 2, 80 to 512 in steps of 16, and 543 to 4095 in steps of 32. To maximize the information gathered for subsequent analysis, all four energy ranges shall be read out in commanded-range order (LEX8 first), and zero-suppression shall be disabled. Charge is injected simultaneously into one column of four GCFEs on each AFEE board.

10. **CALF_COLLECT_CI_SINGLEX16: Determine front-end integral non-linearity and noise with charge injection. Set FLE DACs to their maximum value and Tack delay to optimal value for charge injection. Inject into LE and HE channels. Configure for cross-calibration between LE and HE.**

The electronic gain scale of each energy range shall be measured with charge-injection data. Charge shall be injected simultaneously into a limited number of GCFE chips to minimize the bias introduced into the gain and linearity measurement by cross talk between neighboring GCFEs. This test shall be performed with the FLE DAC set to 127, the maximum possible value. This test is designed to measure the relative gains of the LEX1 and HEX8 channels.

This test shall be performed in muon gain (LE = 5; HE = 0) with the Tack delay set to the optimal value for charge injection with solicited triggers. A modest number of pulses (~50) shall be generated at amplitudes spanning the LEX1 range in a pattern chosen to map the known regions of non-linearity. The default pattern sets the charge injection DAC from 0 to 64 in steps of 2, 80 to 512 in steps of 16, and 543 to 4095 in steps of 32. To maximize the information gathered for subsequent analysis, all four energy ranges shall be read out in commanded-range order (LEX8 first), and zero-suppression shall be disabled. Charge is injected simultaneously into one column of four GCFEs on each AFEE board.

### 4.2.3 calibDAC suite

The calibDAC suite is comprised of a sequence of unit tests.

1. **CALU_INIT: Configure Calorimeter.**

The CAL initialization script shall be executed to ensure that the CAL is powered and begins the calibration suite in a defined configuration.

The default CAL test configuration is given in Table 1 above.

2. **CALF_PEDESTALS_CI: Compute pedestals.**

Pedestals for all energy ranges in all gain settings shall be computed by generating solicited triggers with no charge injection. To avoid crosstalk or chatter, the FLE and FHE discriminators shall be set to their maximum values (i.e. 127). The pedestal is given by the centroid of a Gaussian fit to the observed ADC value from a large number (i.e. ~1000) of triggers at each gain setting. (Because the width of the pedestal distribution in the LEX1 and HEX1 ranges is ~1 bin, Gaussian fitting is ill-conditioned. Therefore, the pedestal centroid and width in these ranges shall be estimated by a simple mean and rms of the 5 ADC bins centered on the pedestal mode.)

Both the centroid and the width of the Gaussian shall be recorded for trending analysis. The pedestal value will be used in subsequent functional tests whenever conversion to energy units is required.

3. **CALU_INIT: Redefine pedestal file.**

The initialization script shall be executed again to load the new pedestal table generated in the previous step.

4. **CALF_GAIN_P01: Calibrate electronic gains with charge injection. Generate *relgain* table.**

The electronic gain of all gain settings for each energy range shall be calculated from charge-injection pulses that are below saturation in the highest gain setting. The mean pedestal-subtracted pulse height for a large number of pulses (i.e. ~200) shall be calculated in each gain setting.

The Tack delay shall be set to the optimal delay for Timed readout computed in this functional test suite. The pedestals subtracted shall be those calculated during this functional test suite.

The output of this test shall be a table expressing the gain of each setting relative to the nominal flight gain (i.e. LE = 5, HE = 13). The relative gain is defined as the ratio of the pedestal-subtracted pulse height in the current gain to that in the nominal flight gain.

The relative gains of all LE gain settings and all HE gain settings shall be recorded for trending analysis.

**5. CALU_INIT: Redefine relative gain table.**

The initialization script shall be executed again to load the new relative gain table generated in the previous step.

**6. CALF_TRG_P03: Calibrate FLE and FHE DAC settings with charge injection.**

The pulse amplitudes at which the FLE and FHE discriminators fire shall be calibrated with charge injection.

This test shall be performed in the nominal flight gain (LE = 5; HE = 13). For each column of GCFEs sequentially, the FLE DAC shall be set to each of the 128 settings spanning fine and coarse ranges, and the charge-injection DAC shall be ramped upward in steps of 3 DAC units, with a small number of pulses (~30) generated at each amplitude. The trigger diagnostic data shall be inspected to determine if the FLE discriminators have fired. If the FLE fires for >50% of the pulses, the corresponding mean LEX8 ADC value shall be recorded. This process shall then be repeated for the FHE DAC in the HEX8 range.

The output of this process is tables of correspondence between FLE/FHE DAC setting and ADC bin number in the nominal flight gain ("*fle2adc*" and "*fhe2adc*").

Note that this calibration is not a precise calibration of the discriminator thresholds in energy units because the charge injection pulse shape is not identical to the scintillation pulse shape; the ratio of fast-shaped to slow-shaped signals is therefore different for charge injection pulses than for scintillation pulses. The correspondence into energy units is calibrated with suite muTrg.

**7. CALF_SUPP_P01: Calibrate LAC DAC settings with charge injection.**

The pulse amplitudes at which the Log-Accept discriminators fire shall be calibrated with charge injection.

This test shall be performed in the nominal flight gain (LE = 5; HE = 13). Because the LAC functions as the logical OR of the discriminators at both end faces of a CDE, the faces must be tested separately. Thus, all Plus-face discriminators shall be tested together, then all Minus-face discriminators. All Plus-face discriminators shall be tested simultaneously. On the face not under test, all LAC DACs shall be set to the maximum value (i.e. 127). The LAC DAC shall be set one of its 128 levels (beginning at 0 and stepping upward to 127), and the charge-injection DAC shall be ramped upward one step at a time, with a small number of pulses (~20) generated at each amplitude, until all LACs have fired. The LEX8 event data for each CDE shall be inspected to determine if the LAC discriminator has fired. For each GCFE, the mean ADC value for the lowest charge-injection setting that causes that GCFE to be present in the event readouts for >50% of the samples shall be recorded.

This process shall then be repeated with the Plus and Minus LAC DACs incremented together to test the functionality of the OR of the CDE faces, i.e. the LAC threshold should be equal to the lesser of the Plus and Minus face thresholds.

The output of this process is a table of correspondence between the LAC DAC setting and LEX8 ADC bin number in the nominal flight gain ("*lac2adc*").

All channels with a lowest-effective LAC DAC setting above 5 MeV shall be recorded as "noisy" in the Noisy Channel table. If this test finds no such channels in the Module under test, a null Noisy Channel table shall be created.

**8. CALF_RNG_P01: Calibrate ULD DAC settings with charge injection.**

The correspondence between the Upper Level Discriminator (ULD) DAC setting and the ADC value at which the range selection is made shall be calibrated with charge injection.

This test shall be performed in the nominal flight gain (LE = 5; HE = 13) with the data read out in one-range, auto-range order. The ULD DAC shall be set one of its 128 levels (beginning at 0 and stepping upward to 127), and the charge-injection DAC shall be ramped upward one step at a time, with a small number of pulses (~20) generated at each amplitude. The ADC values at which LEX8 transitions to LEX1, LEX1 transitions to HEX8, and HEX8 transitions to HEX1 shall be recorded at each ULD DAC setting.

# 5 MUON CALIBRATION

## 5.1 PURPOSE OF MUON CALIBRATION

The goal of muon calibration is primarily the calibration of the "optical gain" of each photodiode, from which the correspondence between ADC bin and energy deposited is established. From this calibration, the following are achieved.

- Optimization of the time delay between trigger and peak hold to give maximal light yield for the ensemble of CDEs in a Module.
- Verification of the calibration in energy units of the FLE and FHE tables generated in the electronic calibration.
- Fitting of the muon peak in each LE and HE photodiode in muon test gain setting. From the muon peak, the *adc2nrgy* table is created.
- Mapping of the light taper and light asymmetry in each CDE as a function of position.

There are two forms of muon calibration, the first with CAL internally triggering ("self-triggering") on muons, and the second with an ancillary detector generating external triggers for the CAL Tower Module. The self-triggered calibration requires no additional hardware, but it results in a modestly biased energy scale. The externally triggered calibration does not create a biased energy scale, and therefore is used to generate the final energy calibration of each channel.

## 5.2 DEFINITION OF MUON CALIBRATION SUITES

The muon calibration suites are comprised of a series test scripts that form a suite executed under LATTE. The suites are outlined below as an ordered list of scripts. The motivation for each script is given in this and subsequent sections, along with a description of the script algorithms and configurations. A detailed definition of each script is given in LAT-TD-01502.

### *5.2.1 Outlines of the muon calibration suites*

The goal of the **muShape** suite is to find the optimal Tack delay for muons under CAL self-triggered readout. The suite shall be comprised of the following test procedures. As defined herein, they are executed sequentially on a single CAL Tower Module. At all times during the calibration, Environmental Monitoring and Housekeeping shall be enabled.

1. CALU_INIT: Initialize the Calorimeter.
2. CALF_SHP_MUONS: Find optimal time-to-peak for muons under CAL self-triggered readout.

The total run time for the muShape suite is approximately 2.5 or 8 hours, depending on the configuration.

The goal of the **muTrg** suite is to calibrate the FLE DAC settings with muons. The suite shall be comprised of the following test procedures. As defined herein, they are executed sequentially on a single CAL Tower Module. At all times during the calibration, Environmental Monitoring and Housekeeping shall be enabled.

1. CALU_INIT: Initialize the Calorimeter.
2. CALF_TRG_P03: Characterize the FLE DAC settings with charge injection (if required by WOA).
3. genFLEsettings_ADC: Generate FLE DAC settings corresponding to ~5 MeV.
4. CALU_INIT: Load appropriate FLE DAC setting and trigger mask.
5. CALU_COLLECT_MU: Collect muons under CAL self-triggered readout. Set FLE DACs to ~5 MeV. Enable even columns of even rows and odd columns of odd rows.
6. CALU_INIT: Load appropriate FLE DAC setting and trigger mask.
7. CALU_COLLECT_MU: Collect muons under CAL self-triggered readout. Set FLE DACs to ~5 MeV. Enable odd columns of even rows and even columns of odd rows.

8. genFLEsettings_ADC: Generate FLE DAC settings corresponding to ~10 MeV.
9. CALU_INIT: Load appropriate FLE DAC setting and trigger mask. Set FLE DACs to ~10 MeV. Enable even columns of even rows and odd columns of odd rows.
10. CALU_COLLECT_MU: Collect muons under CAL self-triggered readout.
11. CALU_INIT: Load appropriate FLE DAC setting and trigger mask. Set FLE DACs to ~10 MeV. Enable odd columns of even rows and even columns of odd rows.
12. CALU_COLLECT_MU: Collect muons under CAL self-triggered readout.
13. CALU_INIT: Restore FLE DAC setting and trigger mask to initial values.

The total run time for the muTrg suite is approximately 4 hours.

The **collectMuons** suite collects muon data (surprisingly enough) under CAL self-triggered readout. It shall be comprised of the following test procedures. As defined herein, they are executed sequentially on a single CAL Tower Module. At all times during the calibration, Environmental Monitoring and Housekeeping shall be enabled.

1. CALU_INIT: Initialize the Calorimeter.
2. CALU_COLLECT_MU: Collect muons under CAL self-triggered readout.

The collectMuons suite is terminated manually after the time specified in the authorizing Work Order.

The self-triggered **MuC** muon calibration is identical to the collectMuons suite, except that it is followed by an on-line analysis to generate approximate CDE response maps. It shall be comprised of the following test procedures. As defined herein, they are executed sequentially on a single CAL Tower Module. At all times during the calibration, Environmental Monitoring and Housekeeping shall be enabled.

1. CALU_INIT: Initialize the Calorimeter.
2. CALU_COLLECT_MU: Collect muons under CAL self-triggered readout.
3. CALF_MAP_MU: Analyze muon data to map CAL CDE response.

This suite is terminated manually after the time specified in the authorizing Work Order.

The goal of the **extShape** suite is to find the optimal Tack delay for muons under externally-triggered readout. The suite shall be comprised of the following test procedures. As defined herein, they are executed sequentially on a single CAL Tower Module. At all times during the calibration, Environmental Monitoring and Housekeeping shall be enabled.

1. CALU_INIT: Initialize the Calorimeter.
2. CALF_SHP_EXT: Find optimal time-to-peak for muons under externally-triggered readout.

The total run time for the extShape suite is approximately 2.5 or 8 hours, depending on the configuration.

The **collectExt** suite collects externally-triggered events. It shall be comprised of the following test procedures. As defined herein, they are executed sequentially on a single CAL Tower Module. At all times during the calibration, Environmental Monitoring and Housekeeping shall be enabled.

1. CALU_INIT: Initialize the Calorimeter.
2. CALU_COLLECT_MU: Collect muons under CAL self-triggered readout.

The collectExt suite is terminated manually after the time specified in the authorizing Work Order.

The **MuCExt** suite is identical to the collectExt suite, except that it is followed by on-line analysis to generate CDE optical response maps. It shall be comprised of the following test procedures. As defined herein, they are executed sequentially on a single CAL Tower Module. At all times during the calibration, Environmental Monitoring and Housekeeping shall be enabled.

3. CALU_INIT: Initialize the Calorimeter.
4. CALU_COLLECT_MU: Collect muons under CAL self-triggered readout.
5. CALF_MAP_MU: Analyze muon data to map CAL CDE response.

This suite is terminated manually after the time specified in the authorizing Work Order.

### 5.2.2 muShape suite

The muShape suite is composed of a sequence of two unit tests. It is designed to find the optimal Tack delay for CAL self-triggered muons. An on-line analysis routine is defined here, but more detailed analysis of the same data sets may be performed subsequently off line.

**1. CALU_INIT: Initialize the Calorimeter**

The CAL initialization script shall be executed to ensure that the CAL is powered and begins the muon calibration in a defined configuration.

The default CAL test configuration is given in Table 1 above.

**2. CALF_SHP_MUONS: Find optimal time-to-peak for CAL self-triggering with muons.**

The LE and HE slow shaping amplifier outputs shall be mapped and the optimal Tack time delay for scintillation pulses under self-triggered readout shall be determined with muons.

This test shall be performed in muon test gain (LE = 5; HE = 0) with the data read out in commanded-range (LEX8 first), four-range mode. The CAL shall self-trigger with CAL-LO enabled and CAL-HI disabled, with the FLE discriminators set to 8 MeV or below. The Tack delay shall be set to each of number of values (e.g. 10, 40, 100, 150, and 200) in sequence. Muons shall be collected for 30 minutes (longer if authorized by the WOA) at each Tack delay setting.

(Two combinations of Tack delay and accumulation time have proved useful in CAL testing: a long program with Tack delays 10, 30, 50, 70, 100, 150, 200, and 250 and an accumulation time of 1 hour at each setting, and the short program listed above.)

The muon data shall then be analyzed at each Tack delay. "Penetrating" muons – viz. those that pass through the top and bottom layers of the CAL Module – shall be selected by requiring that both layer 0 and layer 7 LEX8 ADC values shall be at least 100 bins above pedestal. The CAL-wide total LEX8 and HEX8 pedestal-subtracted ADC values for penetrating muons shall be histogrammed and fit with a log-normal function to find the muon peak. The muon peak shall then be fit as a function of Tack delay – independently for LEX8 and HEX8 – with the following function that describes the output of the GCFE shaping amplifier.

$$y = A\left(1 + (t - t_{pk}) / \tau\right)\exp[-(t - t_{pk}) / \tau]$$

The optimal Tack Delay shall be defined to be average of the $t_{pk}$ values for LEX8 and HEX8.

### 5.2.3 muTrg suite

The muTrg suite is composed of a sequence of 13 unit tests. It is designed to verify the calibration of the FLE discriminators – previously generated by a calibGen suite – with muons. While only a limited number of DAC settings are examined here, in combination with the results of CALF_TRG_P03, the complete energy calibration can be derived.

An outline of the calibration process follows.

This test shall be performed in muon gain (LE = 5; HE = 0). To calibrate the FLE discriminators, the data shall be read out in commanded-range (LEX8 first), 4-range mode to provide cross-calibration in LEX8 and LEX1 ranges. Zero-suppression shall be disabled to ensure that pedestals are registered in the dataset. The CAL shall self-trigger with CAL-LO enabled and CAL-HI disabled. The Tack delay shall be set to the optimal delay for CAL self-triggered readout.

The FLE discriminators shall be set to ~5 MeV, as defined by calibration of the FLE DAC with charge injection. The trigger mask shall be set to enable FLE on the even-numbered columns (i.e. 0, 2, 4, 6, 8, and 10) of the even-numbered X and Y layers (i.e. X0, Y0, X2, and Y2). Muon data shall be collected for one hour. A histogram of each log end that has FLE enabled shall be accumulated. At the same time, a histogram of each enabled log end shall be accumulated for the subset of events where Diagnostic data shows that its layer-end issued a trigger request. Because the overwhelming majority of muons pass through at most one and only one of the enabled CDEs in each layer, it is possible to know unambiguously which FLE caused the layer-end to request a trigger. The ratio of the histograms is then a measure of the FLE trigger efficiency for each enabled GCFE. The trigger threshold shall be defined to be the ADC bin with trigger efficiency > 50%.

To complete the calibration at 5 MeV, this one-hour run shall then be repeated with the FLE enabled only on the complementary channels, i.e. on the odd-numbered columns of the even layers and the even-numbered columns of the odd layers.

This two-step process shall then be repeated with the FLE discriminators shall be set to ~10 MeV.

The total accumulation time for FLE calibration is therefore four hours.

**1. CALU_INIT: Initialize the Calorimeter**

The CAL initialization script shall be executed to ensure that the CAL is powered and begins the suite in a defined configuration.

The default CAL test configuration is given in Table 1 above.

**2. CALF_TRG_P03: Characterize the FLE DAC settings with charge injection (if required by WOA).**

If specified in the authorizing Work Order, the pulse amplitudes at which the FLE and FHE discriminators fire shall be calibrated with charge injection. Otherwise, an existing FLE DAC calibration table will be used in the remainder of the suite.

This test shall be performed in the nominal flight gain (LE = 5; HE = 13). For each column of GCFEs sequentially, the FLE DAC shall be set to each of the 128 settings spanning fine and coarse ranges, and the charge-injection DAC shall be ramped upward one step at a time, with a small number of pulses (~30) generated at each amplitude. The trigger diagnostic data shall be inspected to determine if the FLE discriminators have fired. If the FLE fires for >50% of the pulses, the corresponding mean ADC value shall be recorded. This process shall then be repeated for the FHE DAC.

The output of this process is tables of correspondence between FLE/FHE DAC setting and ADC bin number in the nominal flight gain ("*fle2adc*" and "*fhe2adc*").

**3. genFLEsettings_ADC: Generate FLE DAC settings corresponding to ~5 MeV.**

A table shall be generated of the FLE DAC settings most closely corresponding to 5 MeV energy deposition. If an FLE characterization table was generated in the previous step, the DAC setting shall be found from that table. Otherwise, the DAC setting shall be found from the FLE characterization table specified in the initial CALU_INIT. For purposes of this test, "5 MeV" shall be defined to be 150 ADC bins above pedestal (a typical muon energy deposition of ~11 MeV corresponds to a pulse height of ~ 330 ADC bins).

The output of this process is an FLE DAC setting table.

**4. CALU_INIT: Load appropriate FLE DAC setting and trigger mask. Set FLE DACs to ~5 MeV. Enable even columns of even rows and odd columns of odd rows.**

The CAL initialization script shall be executed to load the "5 MeV" FLE DAC setting table and to set the FLE trigger mask to enable discriminators on the GCFEs of the even columns (i.e. 0, 2, 4, …, 10) of the even rows (i.e. X0, X2, Y0, and Y2) and the odd columns (i.e. 1,3, …, 11) of the odd rows (i.e. X1, X3, Y1, and Y3).

**5. CALU_COLLECT_MU: Collect muons under CAL self-triggered readout.**

Muon data shall be collected for one hour.

This test shall be performed in muon gain (LE = 5; HE = 0). The data shall be read out in commanded-range (LEX8 first), 4-range mode to provide cross-calibration in LEX8 and LEX1 ranges. Zero-suppression shall be disabled to ensure that pedestals are registered in the dataset. The CAL shall self-trigger with CAL-LO enabled and CAL-HI disabled. The Tack delay shall be set to the optimal delay for CAL self-triggered readout.

**6. CALU_INIT: Load appropriate FLE DAC setting and trigger mask. Set FLE DACs to ~5 MeV. Enable odd columns of even rows and even columns of odd rows.**

The CAL initialization script shall be executed to load the "5 MeV" FLE DAC setting table and to set the FLE trigger mask to enable discriminators on the GCFEs of the odd columns (i.e. 1, 3, …, 11) of the even rows (i.e. X0, X2, Y0, and Y2) and the even columns (i.e. 0, 2, …, 10) of the odd rows (i.e. X1, X3, Y1, and Y3).

7. **CALU_COLLECT_MU: Collect muons under CAL self-triggered readout.**

Muon data shall be collected for one hour.

This test shall be performed in muon gain (LE = 5; HE = 0). The data shall be read out in commanded-range (LEX8 first), 4-range mode to provide cross-calibration in LEX8 and LEX1 ranges. Zero-suppression shall be disabled to ensure that pedestals are registered in the dataset. The CAL shall self-trigger with CAL-LO enabled and CAL-HI disabled. The Tack delay shall be set to the optimal delay for CAL self-triggered readout.

8. **genFLEsettings_ADC: Generate FLE DAC settings corresponding to ~10 MeV.**

A table shall be generated of the FLE DAC settings most closely corresponding to 10 MeV energy deposition. If an FLE characterization table was generated in the previous step, the DAC setting shall be found from that table. Otherwise, the DAC setting shall be found from the FLE characterization table specified in the initial CALU_INIT. For purposes of this test, “10 MeV” shall be defined to be 300 ADC bins above pedestal.

The output of this process is an FLE DAC setting table.

9. **CALU_INIT: Load appropriate FLE DAC setting and trigger mask. Set FLE DACs to ~10 MeV. Enable even columns of even rows and odd columns of odd rows.**

The CAL initialization script shall be executed to load the “10 MeV” FLE DAC setting table and to set the FLE trigger mask to enable discriminators on the GCFEs of the even columns (i.e. 0, 2, 4, …, 10) of the even rows (i.e. X0, X2, Y0, and Y2) and the odd columns (i.e. 1, 3, …, 11) of the odd rows (i.e. X1, X3, Y1, and Y3).

10. **CALU_COLLECT_MU: Collect muons under CAL self-triggered readout.**

Muon data shall be collected for one hour.

This test shall be performed in muon gain (LE = 5; HE = 0). The data shall be read out in commanded-range (LEX8 first), 4-range mode to provide cross-calibration in LEX8 and LEX1 ranges. Zero-suppression shall be disabled to ensure that pedestals are registered in the dataset. The CAL shall self-trigger with CAL-LO enabled and CAL-HI disabled. The Tack delay shall be set to the optimal delay for CAL self-triggered readout.

11. **CALU_INIT: Load appropriate FLE DAC setting and trigger mask. Set FLE DACs to ~10 MeV. Enable odd columns of even rows and even columns of odd rows.**

The CAL initialization script shall be executed to load the “10 MeV” FLE DAC setting table and to set the FLE trigger mask to enable discriminators on the GCFEs of the odd columns (i.e. 1, 3, …, 11) of the even rows (i.e. X0, X2, Y0, and Y2) and the even columns (i.e. 0, 2, …, 10) of the odd rows (i.e. X1, X3, Y1, and Y3).

12. **CALU_COLLECT_MU: Collect muons under CAL self-triggered readout.**

Muon data shall be collected for one hour.

This test shall be performed in muon gain (LE = 5; HE = 0). The data shall be read out in commanded-range (LEX8 first), 4-range mode to provide cross-calibration in LEX8 and LEX1 ranges. Zero-suppression shall be disabled to ensure that pedestals are registered in the dataset. The CAL shall self-trigger with CAL-LO enabled and CAL-HI disabled. The Tack delay shall be set to the optimal delay for CAL self-triggered readout.

13. **CALU_INIT: Restore FLE DAC setting and trigger mask to initial values.**

The CAL initialization script shall be executed again to restore the FLE DAC setting and trigger mask tables to their values prior to the start of the muTrg suite.

This completes the muTrg suite. The full analysis of the muTrg data is performed off line. The output of this process is a set of conversion factors between the FLE and FHE calibration tables derived in the electronic calibration (*fle2adc* and *fhe2adc*, in combination with the *adc2nrgy* and *relgain* tables). If the electronic calibrations are well understood, these correction factors should be close to unity. Recall that the electronic calibrations of FLE and FHE were not precise calibrations of the discriminator thresholds in energy units because the charge injection pulse shape is not identical to the scintillation pulse shape; the ratio of fast-shaped to slow-shaped signals is therefore different for charge injection pulses than for scintillation pulses.

### *5.2.4 collectMuons suite*

The collectMuons suite accumulates CAL self-triggered muon data for subsequent analysis.

**1. CALU_INIT: Initialize the Calorimeter**

The CAL initialization script shall be executed to ensure that the CAL is powered and begins the muon calibration in a defined configuration. The FLE DAC settings corresponding to 150 LEX8 ADC bins shall be selected.

The default CAL test configuration is given in Table 1 above – although the default FLE DAC settings table is replaced by the "adc150" table.

**2. CALU_COLLECT_MU: Collect muons under self-triggered readout.**

Muon data shall be collected to calibrate the optical gain of each photodiode and create maps of light taper and light asymmetry.

This test shall be performed in muon test gain (LE = 5; HE = 0). At this gain setting, the muon peak appears at ~5% of full scale in LEX8 and ~3% of full scale in HEX8. The data shall be read out in commanded-range (LEX8 first), 4-range mode to allow simultaneous verification of the LE and HE photodiodes. Zero-suppression shall be disabled to ensure that pedestals are registered in the dataset. The CAL shall self-trigger with CAL-LO enabled and CAL-HI disabled. The Tack delay shall be set to the optimal delay for CAL self-triggered readout.

The suite shall run until manually stopped by the operator. The run time shall be specified in the authorizing Work Order. A run time of 24 hours is sufficient to create light taper and light asymmetry maps with a precision of ~1%.

### *5.2.5 Self-triggered MuC suite*

The self-triggered MuC suite is identical to the collectMuons suite, except that it is followed by an on-line analysis of the accumulated muon spectra. The output of this analysis is a set of CDE response maps and calibration constants compatible with the SAS environment.

**1. CALU_INIT: Initialize the Calorimeter**

The CAL initialization script shall be executed to ensure that the CAL is powered and begins the muon calibration in a defined configuration.

The default CAL test configuration is given in Table 1 above.

**2. CALU_COLLECT_MU: Collect muons under self-triggered readout.**

Muon data shall be collected to calibrate the optical gain of each photodiode and create maps of light taper and light asymmetry.

This test shall be performed in muon test gain (LE = 5; HE = 0). At this gain setting, the muon peak appears at ~5% of full scale in LEX8 and ~3% of full scale in HEX8. The data shall be read out in commanded-range (LEX8 first), 4-range mode to allow simultaneous verification of the LE and HE photodiodes. Zero-suppression shall be disabled to ensure that pedestals are registered in the dataset. The CAL shall self-trigger with CAL-LO enabled and CAL-HI disabled, with the FLE discriminators set to 8 MeV or below. The Tack delay shall be set to the optimal delay for CAL self-triggered readout.

The total muon run time shall be 24 hours, unless otherwise instructed by the authorizing Work Order. This run time is sufficient to create light taper and light asymmetry maps with a precision of ~1%.

**3. CALF_MAP_MU: Analyze muon data to map CAL CDE response.**

Muon data accumulated with CALU_COLLECT_MU shall be analyzed to estimate the light yield and map the light taper and light asymmetry in each CDE. The procedure described here is employed at the CDE assembly level, the PEM assembly level, and here at the CAL Module level.

Muon events shall be analyzed with the Module divided into pairs of X and Y layers, one pair of layers at a time. Events that hit one-and-only-one X CDE and one-and-only-one Y CDE shall be selected. The criteria for "one-and-only-one" hit in a layer shall be LEX8 pulse heights > 100 ADC bins in both ends of one CDE and LEX8 pulse heights < 5σ (σ = pedestal rms) above pedestal in all other CDEs of that layer. The X and Y coordinates of each muon trajectory in the selected layers is thereby pixelized. Histograms of the pedestal-subtracted LEX8, LEX1, HEX8, and HEX1 pulse heights, the LEX8 and HEX8 root-products, the LEX8 and HEX8 light asymmetry, and the LEX8 and HEX8 log-ratio shall be accumulated in each pixel.

The root-product is defined to be the square root of the product of the Plus and Minus face pedestal-subtracted pulse heights.

$$RP = \mathrm{sqrt}(\mathrm{Plus} \times \mathrm{Minus})$$

The light asymmetry is defined to be the ratio of the difference of Plus and Minus face pedestal-subtracted pulse heights to the sum of Plus and Minus face pedestal-subtracted pulse heights.

$$A = (\mathrm{Plus} - \mathrm{Minus}) / (\mathrm{Plus} + \mathrm{Minus})$$

The log-ratio is defined to be the natural logarithm of the ratio of pedestal-subtracted pulse heights from the Plus and Minus faces in the specified energy range.

$$LR = \log(\mathrm{Plus} / \mathrm{Minus})$$

In each pixel, the pulse-height histograms shall be fit with a log-normal function. The muon peak shall be defined to be the peak of the log-normal function, and it shall be assigned an energy deposition of 11.3 MeV, which is the GEANT4-calculated most-probable energy deposition for relativistic sea-level muons passing full through the 1.99 cm height of a CDE. The light taper map for each face of each CDE is therefore the muon peak as a function of pixel number along the length of the CDE.

In each pixel, the light asymmetry and log-ratio histograms shall be fit with a Gaussian. The maps of the light asymmetry and log-ratio are therefore the Gaussian centroids as a function of pixel number along the length of the CDE.

The light taper, light asymmetry, and log-ratio maps shall then be stored in a format compatible with the SAS environment.

### *5.2.6 extShape suite*

The extShape suite is composed of a sequence of two unit tests. It is designed to find the optimal Tack delay for externally-triggered muons. An on-line analysis routine is defined here, but more detailed analysis of the same data sets may be performed subsequently off line.

**1. CALU_INIT: Initialize the Calorimeter**

The CAL initialization script shall be executed to ensure that the CAL is powered and begins the muon calibration in a defined configuration.

The default CAL test configuration is given in Table 1 above.

**2. CALF_SHP_EXT: Find optimal time-to-peak for CAL muons under an external trigger.**

The LE and HE slow shaping amplifier outputs shall be mapped and the optimal Tack time delay for scintillation pulses under externally-triggered readout shall be determined with muons.

This test shall be performed in muon test gain (LE = 5; HE = 0) with the data read out in commanded-range (LEX8 first), four-range mode. The CAL shall trigger on a source external to the CAL (e.g. the TKR, or plastic scintillator paddles). The CAL triggers, CAL-LO and CAL-HI, shall be disabled, and the FLE and FHE discriminator DACs set to 127. The Tack delay shall be set to each of number of values (e.g. 10, 40, 100, 150, and 200) in sequence. Muons shall be collected for 30 minutes (longer if authorized by the WOA) at each Tack delay setting.

(Two combinations of Tack delay and accumulation time have proved useful in CAL testing: a long program with Tack delays 10, 30, 50, 70, 100, 150, 200, and 250 and an accumulation time of 1 hour at each setting, and the short program listed above.)

The muon data shall then be analyzed at each Tack delay. “Penetrating” muons – viz. those that pass through the top and bottom layers of the CAL Module – shall be selected by requiring that both layer 0 and layer 7 LEX8 ADC values shall be at least 100 bins above pedestal. The CAL-wide total LEX8 and HEX8 pedestal-subtracted ADC values for penetrating muons shall be histogrammed and fit with a log-normal function to find the muon peak. The muon peak shall then be fit as a function of Tack delay – independently for LEX8 and HEX8 – with the following function that describes the output of the GCFE shaping amplifier.

$$y = A\left(1 + (t - t_{pk}) / \tau\right)\exp[-(t - t_{pk}) / \tau]$$

The optimal Tack Delay shall be defined to be average of the $t_{pk}$ values for LEX8 and HEX8.

### 5.2.7 collectExt suite

The collectExt suite collects externally triggered events. It is comprised of two unit tests. The third unit provides an immediate, on-line analysis of the muon spectra to generate calibration constants useful for science analysis. It is a simplified version of the off-line muon analysis.

1. **CALU_INIT: Initialize the Calorimeter**

The CAL initialization script shall be executed to ensure that the CAL is powered and begins the muon calibration in a defined configuration.

The default CAL test configuration is given in Table 1 above.

2. **CALU_COLLECT_EXT: Collect muons under externally-triggered readout.**

Muon data shall be collected to calibrate the optical gain of each photodiode without the energy bias introduced by FLE and FHE firing.

This test shall be performed in muon test gain (LE = 5; HE = 0). At this gain setting, the muon peak appears at ~10% of full scale in LEX8 and ~5% of full scale in HEX8. The data shall be read out in commanded-range (LEX8 first), 4-range mode to allow simultaneous verification of the LE and HE photodiodes. Zero-suppression shall be disabled to ensure that pedestals are registered in the dataset. The CAL shall trigger externally on the plastic paddles (or TKR), and the Tack delay shall be set to the optimal value for the external trigger source.

The total muon run time shall be 24 hours, unless otherwise instructed by the authorizing Work Order. This run time is sufficient to create light taper and light asymmetry maps with a precision of ~1%.

### 5.2.8 MuCExt suite

The externally triggered MuCExt suite is comprised of three unit tests. The third unit provides an immediate, on-line analysis of the muon spectra to generate calibration constants useful for science analysis. It is a simplified version of the off-line muon analysis.

3. **CALU_INIT: Initialize the Calorimeter**

The CAL initialization script shall be executed to ensure that the CAL is powered and begins the muon calibration in a defined configuration.

The default CAL test configuration is given in Table 1 above.

4. **CALU_COLLECT_EXT: Collect muons under externally-triggered readout.**

Muon data shall be collected to calibrate the optical gain of each photodiode without the energy bias introduced by FLE and FHE firing.

This test shall be performed in muon test gain (LE = 5; HE = 0). At this gain setting, the muon peak appears at ~10% of full scale in LEX8 and ~5% of full scale in HEX8. The data shall be read out in commanded-range (LEX8 first), 4-range mode to allow simultaneous verification of the LE and HE photodiodes. Zero-suppression shall be disabled to ensure that pedestals are registered in the dataset. The CAL shall trigger externally on the plastic paddles (or TKR), and the Tack delay shall be set to the optimal value for the external trigger source.

The total muon run time shall be 24 hours, unless otherwise instructed by the authorizing Work Order. This run time is sufficient to create light taper and light asymmetry maps with a precision of ~1%.

5. **CALF_MAP_MU: Analyze muon data to map CAL CDE response. (optional)**

This process is a simplified version of the off line, imaged analysis of sea level cosmic muons. It produces a set of calibration constants that may be directly compared with those generated by the off-line process. The off-line process uses imaged muon trajectories from the TKR, when it is available. When the TKR is not available, the off-line process uses the "crystal hodoscope" event selection similar to that described here.

Muon data accumulated with CALU_COLLECT_EXT may be analyzed to estimate the light yield and map the light taper and light asymmetry in each CDE. The procedure described here is employed at the CDE assembly level, the PEM assembly level, and here at the CAL Module level.

Muon events shall be analyzed with the Module divided into pairs of X and Y layers, one pair of layers at a time. Events that hit one-and-only-one X CDE and one-and-only-one Y CDE shall be selected. The criteria for "one-and-only-one" hit in a layer shall be LEX8 pulse heights > 100 ADC bins in both ends of one CDE and LEX8 pulse heights < 5σ (σ = pedestal rms) above pedestal in all other CDEs of that layer. The X and Y coordinates of each muon trajectory in the selected layers is thereby pixelized. Histograms of the pedestal-subtracted LEX8, LEX1, HEX8, and HEX1 pulse heights, the LEX8 and HEX8 root-products, the LEX8 and HEX8 light asymmetry, and the LEX8 and HEX8 log-ratio shall be accumulated in each pixel.

The root-product is defined to be the square root of the product of the Plus and Minus face pedestal-subtracted pulse heights.

$$RP = \mathrm{sqrt}(Plus * Minus)$$

The light asymmetry is defined to be the ratio of the difference of Plus and Minus face pedestal-subtracted pulse heights to the sum of Plus and Minus face pedestal-subtracted pulse heights.

$$A = (Plus - Minus) / (Plus + Minus)$$

The log-ratio is defined to be the natural logarithm of the ratio of pedestal-subtracted pulse heights from the Plus and Minus faces in the specified energy range.

$$LR = \log(Plus / Minus)$$

In each pixel, the pulse-height histograms shall be fit with a log-normal function. The muon peak shall be defined to be the peak of the log-normal function, and it shall be assigned an energy deposition of 11.3 MeV, which is the GEANT4-calculated most-probable energy deposition for relativistic sea-level muons passing full through the 1.99 cm height of a CDE. The light taper map for each face of each CDE is therefore the muon peak as a function of pixel number along the length of the CDE.

In each pixel, the light asymmetry and log-ratio histograms shall be fit with a gaussian. The maps of the light asymmetry and log-ratio are therefore the gaussian centroids as a function of pixel number along the length of the CDE.

The light taper, light asymmetry, and log-ratio maps shall then be stored in a format compatible with the SAS environment.